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INCOMPLETE COMBUSTION IN NATURAL-GAS SPACE HEATERS

BY

G. W. JONES, W. P. YANT, AND
L. B. BERGER

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INCOMPLETE COMBUSTION IN NATURAL-GAS HEATERS

By G. W. Jones, W. P. Yant, and L. B. Berger

INTRODUCTION

Many tests of natural-gas heaters for warming rooms in houses have been made by the Bureau of Mines to determine: 1, What types of heaters, as usually operated, give products of incomplete combustion; 2, why combustion is incomplete; and 3, how, by proper adjustment or change in design, the different types of heaters can be made safer and more efficient.

Not only is there a loss of efficiency and an increased consumption of gas when a heater gives off products of incomplete combustion, but these products consist largely of carbon monoxide (CO), an insidious and treacherous gas, which when present in an atmosphere in amounts as small as 0.15 per cent will cause death. Health and safety require that more than 0.01 per cent carbon monoxide should never be present in air to be breathed, because even this amount will render inert 15 to 20 per cent of the oxygen-carrying capacity of the blood of a person exposed for several hours to such an atmosphere, and may in time lower his vitality so that he becomes more susceptible to disease. Furthermore, this gas can not ordinarily be detected by sight, taste, or smell, and dangerous quantities may be present in the atmosphere of a room without the occupants being aware.

In Ohio during the winter of 1922–23 incomplete combustion products from house heaters[1] caused more than 50 deaths and 100 asphyxiations. Numerous fatalities have occurred in other States, but the exact record is not available. In the Pittsburgh district the writers investigated 10 deaths that were traceable to carbon monoxide liberated from natural-gas heaters. These figures are not given to create the impression that natural-gas heaters are especially dangerous, but to show that cooperation between manufacturers, dealers, and the public is needed to lessen the hazards that exist.

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[1] Hayhurst, E. R., Domestic carbon monoxide poisoning from gas stoves: Amer. Jour. Public Health, vol. 13, 1923, 462 pp.

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The fatalities that have resulted from the use of natural-gas heaters have not been caused by heaters of any one type. Some heaters that caused many deaths were faultily constructed by manufacturers, who did not understand the principles of natural-gas combustion. The publicity given to such fatalities has been difficult to combat by manufacturers who have marketed heaters of similar design but of much better construction.

CAUSES OF LIBERATION OF CARBON MONOXIDE

Fatalities have resulted from one or more of the following causes:

1. Faulty design.
2. Properly designed heaters with too many adjustments to be made by the users.
3. Properly designed heaters with few adjustments, but these deliberately changed by users mainly to get greater rates of gas flow than the heaters can burn efficiently.

To reduce fatalities to a minimum, heaters must first be correctly designed, with as few adjustments as possible, so that chances for improper usage will be reduced. Second, the public must be informed of the danger that may exist if such heaters are not properly operated and must be instructed as to proper manipulation. Publication of this information should not create a general prejudice against natural-gas heaters any more than against other devices that may cause injury through careless use. For example, safety organizations tell pedestrians how to cross streets in heavy automobile traffic and warn them that there is danger of accident unless they follow such instructions. Giving information on the safe operation of natural-gas heaters should not cause the public to stop using them any more than "safety first" education should stop people from crossing streets. In both cases there are dangers, but when safety measures are applied the number of accidents is reduced.

The data herein reported are a compilation of the results from many types of heaters tested and are intended to show the importance of the design of natural-gas heaters to efficient and safe combustion.

COMBUSTION OF NATURAL GAS

As supplied to users in the different regions of the United States, natural gas consists mainly of methane (80 to 90 per cent), ethane (19 to 9 per cent), and a small amount of nitrogen. One volume of methane requires 9.6 volumes of air to burn it completely to carbon dioxide and water vapor, while 16.7 volumes of air is required to burn ethane completely; and the volume of air required to burn 1 volume of natural gas of the above composition is from 10.8 to 10.1.

In general 10 or more volumes of air is required for the complete combustion of 1 volume of natural gas, and whenever less than the above amount is supplied to the gas, products of incomplete combustion are formed and carbon monoxide is liberated, as shown by the following equation:

1 volume of natural gas+less than 10 volumes of air=combustion products
($CO_2+H_2O+CO+H_2+CH_4$+"gas fumes")

The relative proportions of the combustion products depend on the amount of air supplied per volume of natural gas. The more nearly this value approaches 10 or more volumes the more complete is the combustion. When combustion is complete, water vapor and carbon dioxide only are liberated.

The amounts of carbon dioxide that may accumulate in a room where a heater will burn have no marked harmful physiological effects other than to increase the rate of breathing. Tests of heaters made in a closed room showed (see Table 1) that when the carbon dioxide approximates 3 per cent (1.5 to 4.4, depending upon the type of heater used) the percentage of oxygen become so low that the flames are extinguished.

FORMATION OF WATER VAPOR

For every volume of natural gas burned completely there is produced about 2 volumes of water vapor which, unless removed through a flue connection, increases the humidity (water-vapor content) of the room atmosphere until the air finally becomes saturated. Under these conditions air in a room feels "stuffy." Further generation of water vapor makes the atmosphere more than saturated, and the excess water vapor condenses on the windows, walls, and furniture, more especially on objects whose temperatures are lowest.

Some persons have the erroneous idea that when natural gas is burned and water condenses out the gas is full of water. The original gas usually carries less than 2 per cent of water vapor, and the greater part of the water vapor is formed during the combustion process only. In fact, when natural gas is burned, the greater the amount of water vapor formed the greater the heat generally liberated. The amount of water vapor formed is fairly large. For example, the natural gas used at Pittsburgh sells at 60 cents per 1,000 cubic feet; for every 60 cents' worth of gas burned about 10 gallons of water is produced. Too much condensation of water vapor softens the glue in articles of furniture, which eventually fall apart in consequence. For this reason alone, to get rid of objectionable water vapor, natural-gas heaters should be connected to flues.

GASES PRODUCED BY INCOMPLETE COMBUSTION OF NATURAL GAS

When combustion occurs with an insufficient supply of air, incomplete combustion products, such as carbon monoxide, methane, hydrogen, and "gas fumes," are formed in addition to carbon dioxide and water vapor.

HYDROGEN AND METHANE

The hydrogen and methane are present in small amounts and do not affect the human body.

GAS FUMES

When gas stoves and heaters are first lighted, especially if the flames come in contact with cold surfaces, characteristic gas-fume odors are produced, which, when present in large enough amounts, irritate the eyes, causing them to water, and attack the mucous membranes of the throat and nasal passages. Although they have never been identified definitely, these odors are due mainly to aldehyde vapors; and it is these vapors that usually are confused with carbon monoxide. A heater that gives off gas fumes is usually suspected of liberating carbon monoxide.

To determine what proportions of these vapors are detectable, known mixtures of aldehyde vapors were prepared in the closed room for testing the heaters. The tests showed that the odor could be detected when only 0.0005 per cent, or 5 parts per million, was present; and a very strong odor, which made the eyes smart, was produced when the concentration reached 0.01 per cent, or 100 parts per million. It will be seen, therefore, that the sense of smell can detect a minute quantity of gas fumes, one so small as to be almost nondetectable by chemical means. These small quantities of gas fumes, which are occasionally present in the atmosphere in which a heater is burning, are probably too small to have any harmful effect except the slight discomforts noted. However, in closed rooms where incomplete combustion products accumulate in large amounts (as in serious cases of gassing) these fumes may be decidedly deleterious through irritation of the respiratory passages.

CHARACTERISTICS OF CARBON MONOXIDE

Aside from deaths caused by explosions and burns, fatalities from natural-gas heaters are caused by the one gas, carbon monoxide, which is liberated when combustion is incomplete. This gas is also present in automobile exhaust gas and in the atmosphere of mines after explosions and during fires, causing many deaths each year.

Nature has endowed human bodies with five means of detecting danger—sight, hearing, taste, smell, and touch. Carbon monoxide is a colorless gas; it can not be detected by the eyes, ears, tongue, or fingers. Although there is some relation between gas-fume odors and the liberation of carbon monoxide,[3] by itself carbon monoxide has no odor. Since our senses may not protect us, carbon monoxide is an insidious and a very dangerous gas and possible exposure should be avoided.

Human bodies require an ample supply of oxygen, and for comparison may be likened to natural-gas heaters. Carbon and hydrogen are supplied to the heater in the form of natural gas, which combines with oxygen to generate light and heat. In a similar manner the body is supplied with carbon and hydrogen in the form of food, which in turn is oxidized by oxygen supplied through the lungs and the blood. This process of combustion generates heat to keep the body warm and enable it to do work. The blood carries oxygen from the lungs to parts of the body that need it.

EFFECT OF CARBON MONOXIDE ON THE BODY

The effect of carbon monoxide on the body can be shown if one thinks of the blood as a complex liquid that contains millions of particles called corpuscles, which may be likened to little boats floating in the blood stream. The boats have on board an iron compound called hemoglobin, which has an attraction for oxygen. These little boats come into the lungs, take on a cargo of oxygen, and carry it to the parts of the body that need oxygen. After depositing its oxygen cargo the blood takes on waste products from the body (mainly carbon dioxide), and returns to the lungs where these products are discharged and more oxygen is taken on board.

What happens when a very small amount of carbon monoxide is present in the air which is breathed into the lungs? The hemoglobin on board the little boats likes carbon monoxide about three hundred times as well as it does oxygen. In other words, one carbon monoxide molecule in a crowd of 300 oxygen molecules has as great a chance of getting on the boats as all the oxygen molecules put together. If the carbon monoxide and oxygen molecules are in the proportions just stated, 50 per cent of these little boats would in time be loaded with carbon monoxide molecules, which have "round-trip tickets" and do not get off unless crowded out by larger proportions of oxygen. Thus, they prevent the proper amount of oxygen being carried to parts of the body that need it. Continued exposure to 0.01 per cent of carbon monoxide will cause about 17 per cent of these boats to be filled with carbon monoxide, so that the remaining 83 per cent must do the work of carrying oxygen which the original 100 per cent did. The blood transportation system then becomes overtaxed and inadequate, and if this amount of carbon monoxide continues, a run-down condition of the body may result.

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[3] Jones, G. W., Berger, L. B., and Holbrook, W. F., Hazards from carbon monoxide given off by house heaters burning natural gas: Tech. Paper 337, Bureau of Mines, 1923, pp. 25.

When an exposed person gets into fresh air the preponderance of oxygen eventually drives out all of the carbon monoxide, although much more slowly than it is taken up by the blood.

Carbon monoxide is thus seen to have great reactivity with the blood; and for ordinary conditions in the home, where the occupants may be exposed almost continually to this gas, the concentration of carbon monoxide in amounts greater than 0.01 per cent should not be allowed.

TYPES OF HEATERS THAT LIBERATE CARBON MONOXIDE

The conclusions obtained in this report were partly derived from tests made in a closed room[3] and partly from tests in which the heaters were supplied with normal air containing 20.9 per cent oxygen.[4] The procedure and methods of conducting the tests are given in the reports cited.

All of the different makes of heaters could not be tested, so only certain representative types were chosen. Occasionally several heaters of the same type were tested in order that conclusions could be drawn more accurately.

Table 1 presents in summarized form the results obtained in the closed-room tests of most of the different types of heaters examined. The closed-room tests were supplemented by many tests of normal air outside the chamber, where the liberation of carbon monoxide from the heaters was appreciably affected by orifice adjustment, air-gas ratio, and gas pressure. In general, the tests have shown that any of the natural-gas heaters tested will liberate carbon monoxide under certain conditions; in other words, there are no fool-proof natural-gas heaters. The amounts liberated vary over wide limits, as shown in Table 1, from an insignificant quantity to over 30 per cent of the volume of natural gas used. (Test 5, Table 1.)

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[3] Jones, G. W., Berger, L. B., and Holbrook, W. F., work cited.

[4] Jones, G. W., Yant, W. P., and Berger, L. B., Combustion products from a radiant-type heater and suggestions regarding its operation: Reports of Investigations, Serial 2443, Bureau of Mines, 1923.

TABLE 1.—*Summarized results of tests of different types of natural-gas heaters in a closed room of 1,000 cubic feet capacity, without ventilation*

Test No.	Type of heater	Gas rate, per hour	Composition of atmosphere in room at point when flame was extinguished			Time of burning	Average CO liberation per hour	Remarks
			O_2	CO_2	CO			
		Cubic feet				*Minutes*	*Cubic feet*	
1	Lava tip, yellow flame	20.1	17.67	1.95	0.00	46	0.0	Free-burning flame.
2	do	15.7	17.67	2.02	.00	60	.0	Do.
3	do	10.4	16.79	2.38	.00	116	.0	Do.
4	do	5.1	17.22	2.11	.00	235	.0	Do.
5	do	21.3	15.13	2.71	.63	57	6.6	Flame impinging on reflector.
6	Blue-flame reflector	20	14.50	3.07	1.72	152	6.8	Solid guard over front of heater.
7	do	15	14.68	3.10	.71	155	2.8	Do.
8	do	10	14.64	3.51	.20	206	.6	Do.
9	do	5	14.45	3.62	.13	429	.2	Do.
10	do	20	15.66	3.00	.05	82	.4	Guard removed.
11	Metal-inclosed blue flame No. 1.	14.7	13.80	3.93	.21	142	.9	
12	do	10	13.59	3.97	.09	200	.3	
13	do	5	15.07	3.28	.07	347	.1	
14	Metal-inclosed blue flame No. 2.	15	16.00	2.76	.09	92	.6	Circular bathroom type.
15	do	10	16.20	2.62	.16	139	.7	
16	do	5	16.16	2.69	.08	300	.2	
17	Metal-inclosed blue flame No. 3.	11.3	16.77	2.33	.12	100	.7	Canister in flue for removing fumes.
18	do	5	16.94	2.28	.00	235	.0	
19	do	10.6	18.40	1.47	.06	72	.5	Canister removed.
20	do	9.7	17.11	2.18	.08	111	.4	After using 3 months. Canister on heater.
21	Radiant type No. 1	20	13.83	3.92	.32	111	1.7	10-radiant type.
22	do	15	13.89	3.93	.33	144	1.4	
23	do	10	14.27	3.81	.20	206	.6	
24	do	5	16.40	2.70	.00	275	.0	
25	Radiant type No. 2	20	14.86	3.36	.30	103	1.7	
26	do	15.2	13.61	3.96	.43	150	1.7	
27	do	9.5	13.85	3.98	.14	245	.3	
28	do	5	15.43	3.12	.20	355	.3	
29	Radiant type No. 3	15.6	13.32	4.22	.26	187	.8	10-radiant type.
30	do	15	13.11	4.38	.17	195	.5	
31	do	17	14.60	3.50	.18	169	.6	Maximum rate.
32	Radiant type No. 4	9.8	14.79	3.35	.22	208	.6	5-radiant bathroom type.

WHY CARBON MONOXIDE IS LIBERATED BY NATURAL-GAS HEATERS

The two main reasons why natural-gas heaters liberate carbon monoxide were found to be (1) not enough air supplied to the burning gas to give complete combustion, and (2) attempts to burn too large a volume of gas in a given space. Manufacturers should realize that natural gas requires a large amount of air for complete combustion; in fact, about twice as much as artificial gas. A heating device properly designed for burning artificial gas may therefore prove decidedly unsuitable for burning natural gas.

HEATERS TESTED BY BUREAU OF MINES

The heaters which the Bureau of Mines has tested may, for convenience, be divided into the four following classes:

Type	Air supply
1. Luminous flame, free-burning type	No primary air supply.
2. Blue flame, reflector type	Primary air supply.
3. Blue flame, metal-inclosed type	Do.
4. Nonluminous flame, radiant type	Do.

TYPE 1, LUMINOUS FLAME, NO PRIMARY AIR SUPPLY

The ordinary lava-tip yellow-flame heater is the most representative of the luminous flame type, and the simplest of all in construction and operation. No primary air is added to the gas before its combustion. All of the combustion occurs on the outer surfaces of the flame, and naturally it is slow and at a lower temperature than when primary air is added to the gas before combustion.

Tests have shown that as long as the flame burns without coming in contact with surfaces—the copper reflector, for example—combustion is practically complete, and carbon monoxide is not produced in quantities greater than 0.02 per cent,[4a] a fact that holds true even when the percentage of oyxgen is so reduced that the flame is extinguished. (Tests 1, 2, 3, and 4, Table 1.) However, if the burning flame touches the reflector dangerous quantities of carbon monoxide are formed. In one test (No. 5, Table 1), when a heater was operated at the rate of 21.3 cubic feet per hour, 6.6 cubic feet of carbon monoxide was formed, equivalent to 31 per cent of the natural gas used. A heater burning under these conditions would very soon produce dangerous atmospheres in almost any room in which it stood. Tests in a closed room and in normal air have shown that for the efficient operation of a heater of this type the flame should be free-burning, not over 6 to 8 inches long, potected from drafts, and supplied with plenty of air for combustion.

SUGGESTIONS FOR A PROPERLY DESIGNED HEATER OF TYPE 1

Figure 1 shows the essential features which should be incorporated in a heater of this type to give efficient combustion, and may be summarized as follows:

1. The burner *a* should be so constructed that the flames are directed slightly downward from the horizontal and away from the reflector *b* above the burner. This arrangement permits better mixing of the gas with the incoming air and prevents the flame from being blown against the reflector when drafts are produced; for example, when a door in the room is opened suddenly.

[4a] This 0.02 per cent is based on air-free products of combustion, i. e., undiluted gases coming from the appliance, and it does not mean the 0.02 per cent in the room. When the above 0.02 per cent would be diluted with the amount of air necessary from the standpoint of oxygen required to sustain life or good health the amount of carbon monoxide would be negligible.

2. The reflector *b* should be far enough above and back of the burner so that the flame can not strike against it at any gas flow at which it may be used.

3. The angle of approach *c* of the reflector below the burner should not be so abrupt as to interfere with the air supply reaching the burning gas.

4. An orifice, *d*, should be placed between the gas cock and the burner ports so that the user can not operate the heater at excessive gas rates. (This is very important.)

5. The burner should be riveted or welded to the heater *e* so that the user can not accidentally turn the burner ports and so allow the flame to impinge on the reflector.

6. The opening *f* between the reflector and front panel of the heater should be large enough to carry off the combustion products and thereby prevent smothering of the flame, which would result if these products were allowed to accumulate in the heater.

7. An open wire guard, *g*, should be placed across the front of the heater to prevent garments from being ignited by coming in contact with the flame.

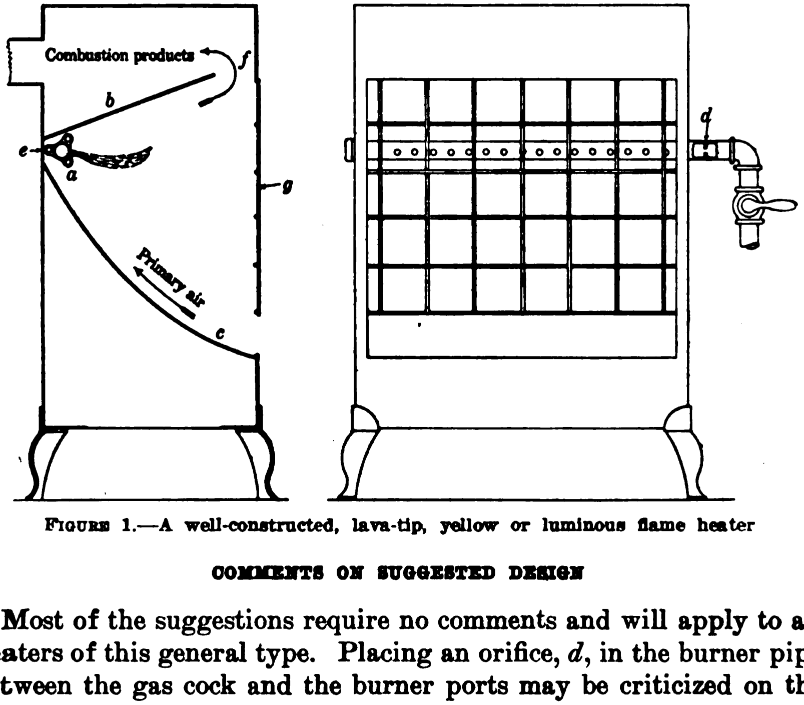

FIGURE 1.—A well-constructed, lava-tip, yellow or luminous flame heater

COMMENTS ON SUGGESTED DESIGN

Most of the suggestions require no comments and will apply to all heaters of this general type. Placing an orifice, *d*, in the burner pipe between the gas cock and the burner ports may be criticized on the grounds that during periods of low-gas pressure the user will be unable to get enough gas. Practically every case of fatal carbon monoxide poisoning in the Pittsburgh district which the writers investigated during the winter of 1922–23 was caused by the use of orifices that were too large for a heater of given size. It is much better to place orifices in the heater so that excessive use of gas can not result, and in turn to recommend to prospective purchasers of heaters that heaters of larger size are necessary to heat a given room rather than to buy or sell undersize heaters with oversize orifices, which may be operated at excessive gas rates and perhaps with fatal results.

This argument applies to each of the other type which are described later.

TYPE 2, BLUE FLAME, PRIMARY AIR SUPPLY, REFLECTOR TYPE

Only one heater of the blue-flame reflector type was tested. In this type a certain amount of primary air is mixed with the gas before it issues from the burner ports. The most common heaters are those having a perforated cylinder burner with an asbestos back or reflector. Others have Bunsen burners from which the flame impinges on an asbestos back.

In the discussion of type 1 it was emphasized that a yellow-flame heater should burn without the flame coming in contact with metal or other surfaces; in heaters of type 2 the flame burns partly in contact with surfaces, yet conditions are somewhat different. In type 1 heaters no primary air is added to the gas before combustion, but in type 2 heaters at least part of the air needed for combustion is introduced with the gas before it reaches the burner ports, thus necessitating a smaller amount of secondary air to complete the combustion. Under these conditions little carbon monoxide is liberated if enough secondary air gets to the burning gas; at least this held true in the burner tested. However, if the amount of primary air added with the gas is reduced enough, eventually the flame would become luminous and carbon monoxide would be liberated. The relative liberation of carbon monoxide when a flame with a small amount of primary air burns in contact with different materials—copper or asbestos, for example—has not been investigated; that is, it is not known to what extent the primary air-gas ratio can be reduced without liberating harmful quantities of carbon monoxide. It is very important that the secondary supply is not restricted, as shown by tests 6, 7, 8, and 9, Table 1. The combustion on the other hand is good if provision is made for enough secondary air to get to the burning gas. (Test 10, Table 1.)

SUGGESTIONS FOR A WELL-DESIGNED HEATER OF TYPE 2

Figure 2 shows certain desirable features which it is advisable to incorporate in a heater of this type to give good combustion. The design and construction are not intended to follow that given in detail; the design merely serves to emphasize essential features of construction, which may be summarized as follows:

1. The heater is shown with an open front that has a wire guard, *a*, which is desirable to allow an ample supply of secondary air to reach the burning gas, giving complete combustion. In one test of such a heater that had a solid mica and metal guard over almost the whole front (test 6, Table 1) the

carbon monoxide in the room reached the exceedingly dangerous concentration of 1.72 per cent after the heater burned 2 hours and 32 minutes, the time when the flame went out. The oxygen had then dropped to 14.5 per cent. A solid guard should never be placed over the front of a heater, especially one of this type, because it smothers the flame and prevents enough secondary air to give complete combustion from reaching the flame. When the test was repeated under the same conditions, but with the guard removed (test 10, Table 1), only a small amount of carbon monoxide was produced.

2. The air-injecting tube *b* should be constructed to give 4 or more volumes of primary air to 1 of gas, which can be done by designing the heater according to directions given by the United States Bureau of Standards.[5] This point, however, is not so essential as with some of the types described later.

3. The opening *c* between the top of the reflector back wall and the top should be large enough to carry off the combustion products easily and quickly. If these products are repressed, the secondary air is likewise repressed, and the gas may not be completely burned.

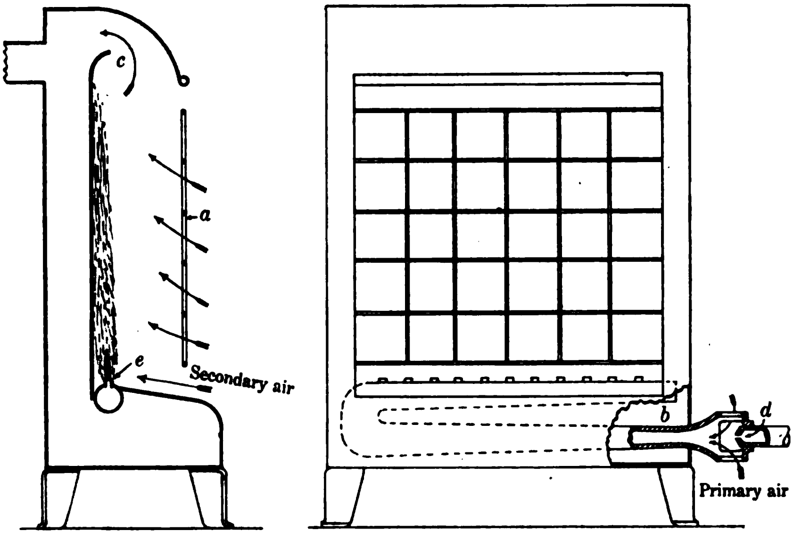

FIGURE 2.—A well-constructed, blue-flame, reflector-type heater

4. The gas orifice *d* should not be too large for the size of the heater, because if it is the user may operate the heater so that the flame extends above the entire back wall, thus producing carbon monoxide. Manufacturers should provide a fixed orifice which will not give excess flow of gas at the maximum gas pressure at which the heater may be used.

TYPE 3, BLUE FLAME, PRIMARY AIR SUPPLY, METAL INCLOSED

The metal-inclosed blue-flame heater with primary air supply differs from heaters of type 2 in that the gas is burned within a metal grid having holes through which the combustion products escape instead of the flame impinging against a reflector. Type 3 comes under the group of free-burning heaters, if the gas rate does not exceed a certain value. This type was found to give complete combustion when supplied with normal air, unless the flame that resulted from excessive gas rates or low primary air-gas ratios came through the holes in the metal grid.

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[5] Berry, W. M., Brumbaugh, I. V., Moulton, G. F., and Shawn, G. B., Design of atmospheric gas burners: Bureau of Standards Technol. Paper 193, 1921, 62 pp.

SUGGESTIONS FOR A WELL-DESIGNED HEATER OF TYPE 3

Three different heaters of this type were tested, and the principal factors to bear in mind, if complete combustion is to be obtained, are indicated in Figure 3 and summarized below:

1. Particular care should be taken to have orifice *a* of the proper size with this type of heater. If it is too large the user may operate at too high a gas rate, so that flames come through the holes in the metal grid, under which conditions the heater is especially dangerous. The orifice should only be large enough to give the proper gas flow at the highest gas pressure available. If the orifice is too large the user may adjust it properly before retiring for the night, then perhaps the gas pressure rises after midnight, when the general demand for gas in the city is less, the gas flow increases accordingly, and the heater liberates dangerous quantities of carbon monoxide.

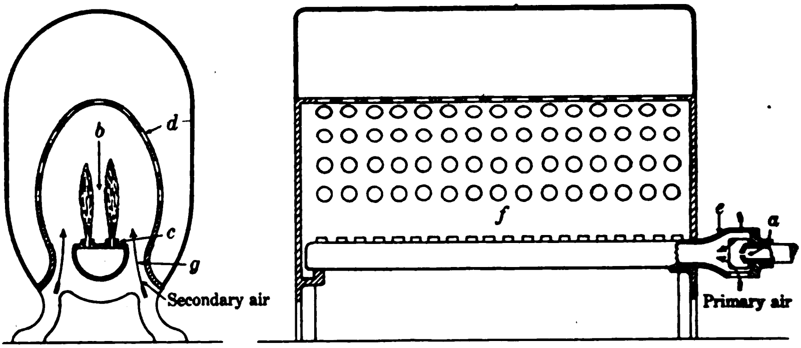

FIGURE 3.—A well-constructed, blue-flame, metal-inclosed heater

2. There should not be more than two rows of gas ports between the secondary air-supply ports *g*. If there are more than two rows—say, four rows—the secondary air ports should be introduced through the middle of the burner. If not, the flames from the inner rows do not get secondary air enough to complete combustion. When enough secondary air can not get to the gas readily, the flames extend in length and come through the holes in the grid, thus liberating carbon monoxide.

3. The burner ports *c* should be raised slightly so that secondary air is drawn into the gas the instant it leaves the burner ports, thus speeding up combustion and completing it in shorter time.

4. The metal grid *d* should be far enough from the flames so that they do not pass through when operated at maximum gas rates. There should be enough holes in the metal grid surrounding the flames to carry off the combustion products quickly and easily, so that the flames are not smothered.

5. The primary-air-injecting tube *e* should be designed to give a high air-gas ratio, which is very important with this type of heater. A flame has the highest rate of flame propagation at or near the point when just the right

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amount of oxygen is present to give complete combustion; for natural gas this would be at an air-gas ratio of about 10 to 1. If the rate of burning is highest at this point, the length of the flame for a given gas flow will be shortest. Any divergence from the ratio needed for complete combustion will cause the flames to lengthen and perhaps pass through the grid. Operating a heater of this type at the 10:1 air-gas ratio might present difficulties due to gas blowing from the ports or flashbacks into the air-injecting tubes. However, some of the heaters tested gave air-gas ratios that ranged from only 2 to 4 volumes of air to 1 of gas, when by increasing the air-gas ratio to 6 or 8 they would operate just as satisfactorily and give good combustion. When heaters are operating at higher air-gas ratios, the proportion of throat area to port area must be kept within certain limits to insure good operation. These points have been very carefully worked out by the Bureau of Standards.[6]

6. To prevent children from being burned and garments catching on fire a guard, *f*, containing an ample number of holes should surround the inner grid *d*, which may become red hot during operation.

7. The secondary air ports *g* should be large enough to supply plenty of secondary air to the burning gas within the metal grid.

TYPE 4, NONLUMINOUS FLAME, PRIMARY AIR SUPPLY, RADIANT TYPE

The radiant type of heater has gained popularity during the last few years, due to its cheerfulness, method of heat distribution, and general neatness. Its adjustment and construction are rather complicated in comparison with the other types just discussed. At present the radiant method of heating is in its infancy, and numerous firms have rushed into the business of manufacturing heaters without considering the fundamental principles of combustion. As a result, many types do not give complete combustion as commonly operated, and carbon monoxide is liberated. Many such heaters have not been properly built and others have too many adjustments that are left to the users' intelligence to operate.

The average user knows very little of combustion processes and sometimes will not even follow the directions supplied with a heater. The prettiest flame in a radiant-type heater is not always that which gives complete combustion. Occasionally a user has deliberately changed the heater to suit his fancy. For example, he substitutes oversize orifices to burn more gas. This latter manipulation in itself is very bad practice, since only a given amount of gas can be burned in a given space under the best conditions, and when this amount is exceeded without corresponding increases of air supply incomplete combustion must result.

Six types of radiant heaters have been tested. The two main causes of liberation of carbon monoxide have been: First, the use of too large orifices, through which more gas enters the radiants than can be burned in the given space; and second, poorly constructed air-injecting tubes that give too low a primary air-gas ratio and thus

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[6] Berry, W. M., Brumbaugh, I. V., Moulton, G. F., and Shawn, G. B., work cited.

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decrease the safe capacity of the stove. Provision for secondary air getting to the flame is also important. Improvements in the shape and design of the radiants were not considered to be within the scope of this investigation and are therefore not discussed.

WHAT TYPES OF RADIANT HEATERS LIBERATE CARBON MONOXIDE?

Of the six types of radiant heaters tested all could be made to liberate carbon monoxide by changing the adjustments on the heater as the average user might do without knowing the reason for the changes; however, the amount liberated by the different heaters varied over wide limits.

WHY RADIANT HEATERS LIBERATE CARBON MONOXIDE

Radiant heaters liberate carbon monoxide whenever the gas flow becomes so high that the combustion space is not large enough for burning the gas admitted.

The amount of gas that can be burned in a radiant heater depends mainly on the size and construction of the radiants and the amount of primary air introduced with the gas. The radiants on the heaters tested were much alike in size and shape, and the highest quantity of gas that could be completely burned when enough air was present to give complete combustion was not more than 1.8 cubic feet of natural gas per hour per radiant. With a 10-radiant heater the gas rate should never be over 1.8 cubic feet per hour, and if the heater does not have a well-constructed air injector much less than this amount can be burned.

PRIMARY AIR SUPPLY

As stated above, the air-gas ratio of the primary air supply affects the completeness of combustion for any given gas rate. A gas-air mixture has the highest rate of flame propagation at or near the ratio for complete combustion. The point of highest rate of flame propagation will, for a given gas rate, consume the gas more quickly, and therefore the flame will be shorter. Any divergence from this perfect mixture will cause the flames to lengthen and the gas will require a longer time for burning. In view of this the combustion should be best and quickest at the air-gas ratio for complete combustion. Tests of the different radiant heaters showed that for most adjustments the air-gas ratio does not reach that for complete combustion, except when gas rates are low and orifice pressures high. For all other adjustments the air-gas ratio is less.

The ideal condition for complete combustion (10 to 1 air-gas ratio) should be approached as nearly as possible, especially at higher rates, and manufacturers of the heaters should keep this condition in mind.

EFFECT OF ORIFICE PRESSURE ON THE AIR-GAS RATIO

The effect of the gas-orifice pressure on the air-gas ratio and liberation of carbon monoxide from a typical radiant heater is shown in Table 2.

Table 2.—*Effect of orifice pressure on the air-gas ratio and liberation of carbon monoxide for a given gas rate (all tests made with the same radiant heater)*

Gas rate per hour	Orifice pressure of water	Air-gas ratio	Carbon monoxide in combustion products, air-free basis by volume
Cubic ft.	*Inches*		*Per cent*
20	1.7	6.6	0.91
20	2.8	7.7	.31
20	3.4	7.1	.48
20	5.2	8.1	.08
15	1.0	6.3	.33
15	1.6	7.3	.18
15	2.9	8.1	.00
15	3.7	8.4	.00
15	4.7	8.7	.00
15	5.7	9.0	.00
10	.5	5.7	.18
10	1.0	7.0	.00
10	1.7	7.8	.00
10	3.9	8.8	.00
10	5.6	9.9	.00
10	6.1	10.9	.00
5	.3	6.4	.00
5	.9	8.3	.00
5	1.8	8.8	.00
5	3.9	11.2	.00
5	5.5	14.4	.00

Table 2 shows a series of tests in which the gas rate was kept constant and the different orifice pressures were obtained by adjusting both the needle valve and the gas cock to give the pressure desired. It will be seen that for any gas rate the orifice pressure and air-gas ratio increase simultaneously, and the liberation of carbon monoxide decreases. In the first series of tests at a gas rate of 20 cubic feet, raising the orifice pressure from 1.7 to 5.2 and the air-gas ratio as a result of this change from 6.6 to 8.1 reduced the liberation of carbon monoxide from 0.91 to 0.08 per cent. If the intake-air injector could be designed to entrain 9 volumes of air to 1 of gas at all gas rates, there should be no liberations of carbon monoxide with this heater at the above gas rate.

At the rate of 15 cubic feet at 1-inch orifice pressure the carbon monoxide in the combustion products (air-free basis) was 0.33 per cent. When the orifice pressure was increased to 2.9 inches no carbon monoxide was liberated. At the gas rates of 10 and 5 cubic feet the results are comparable to the above.

The main point to be observed from these results is that if a radiant heater is adjusted by opening the gas cock completely and then regulating the gas rate from the needle valve so that the gas pressure from the mains is not appreciably reduced in passing through the gas cock—that is, making the orifice pressure as high as possible—then for any given gas rate the air-gas ratio is higher and the liberation of carbon monoxide is at a minimum.

Table 3 shows tests in which the orifice pressures were kept constant and only the gas rate was changed. It will be seen that for a given gas-orifice pressure the air-gas ratio falls and the liberation of carbon monoxide tends to increase as the gas rate is increased.

From these Tables 2 and 3 the reader will note that no matter how well the heater may be designed it can not be made to operate to give a constant air-gas ratio at varying gas rates and orifice pressures. Moreover, at high gas rates the air-gas ratio falls, whereas in order to give complete combustion the air-gas ratio should remain constant, or, if possible, should increase.

TABLE 3.—*Effect of gas rate on the air-gas ratio when the orifice pressure remains constant (all tests made with the same radiant heater)*

Orifice pressure of water	Gas rate per hour	Air-gas ratio	CO in combustion products, air-free basis by volume
Inches	*Cubic feet*		*Per cent*
1	5	8.8	0.00
1	10	7.4	.00
1	15	6.3	.33
1.8	5	8.7	.00
1.8	10	8.2	.00
1.8	15	7.4	.14
1.7	20	6.6	.91
3.9	5	11.2	.00
3.7	10	9.2	.00
3.7	15	8.4	.00
3.4	20	7.1	.48
5.5	5	14.4	....
5.6	10	9.9	.00
5.8	15	9	.00
5.6	20	8.9	.04

When less than the amount of primary air necessary to give complete combustion is introduced with the gas, incomplete combustion products are formed within the radiant.

To get a high air-gas ratio the air injector should be constructed according to the directions given by the Bureau of Standards.[7]

Users should be instructed to operate the heater as much as possible with the needle-valve or orifice adjustment. The effect of operating a radiant heater from the needle valve and gas cock is given in Table 4. The table shows that whenever the heater was operated from the needle valve the air-gas ratio was increased and the liberation of carbon monoxide decreased.

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[7] Berry, W. M., Brumbaugh, I. V., Moulton, G. F., and Shawn, G. B., work cited.

TABLE 4.—*Effect of adjustment of a radiant-type heater by the gas-cock and by the needle-valve or orifice adjustment*

Gas rate per hour	Size of orifice, diameter	Line pressure of water	Regulation by—			
			Needle valve		Gas cock	
			Air-gas ratio	CO	Air-gas ratio	CO
Cubic feet	*Inches*	*Inches*		*Per cent*		*Per cent*
20	0.089	6	8.1	0.15	7.7	0.55
20	.104	6	8.9	.07	6.6	1.32
15	.089	6	9.0	.00	7.4	.02
15	.104	6	8.0	.00	6.3	.04
10	.089	6	10.9	.00	7.1	.00
20	.104	4	8.9	.07	6.6	1.32
15	.104	4	7.8	.05	6.2	.31
15	.089	4	8.4	.00	7.4	.01
10	.104	4	9.2	.00	5.8	.00
10	.089	4	8.8	.00	7.4	.00
5	.104	4	11.2	.00	5.7	.00
5	.089	4	12.2	.00	6.4	.00
15	.104	2	7.3	.25	6.3	.44
10	.104	2	8.2	.00	5.9	.05
10	.089	2	7.8	.00	7.0	.00
5	.104	2	8.7	.00	5.7	.00
5	.089	2	8.7	.00	6.3	.00

The gas rate and gas pressure were kept constant in each of the above tests. One test was made with the gas cock wide open and the needle valve closed to give the desired gas rate, then the test was repeated under the same conditions, with the needle valve open as far as possible and the gas cock closed to give the same gas rate.

The table shows that for the higher gas rates more carbon monoxide is liberated if the heater is adjusted from the gas cock, while changing the method of adjustment and making the adjustment from the needle valve will largely eliminate the liberation of carbon monoxide.

SECONDARY AIR SUPPLY

The necessity of a secondary air supply is shown by the analyses of gases taken within a glowing radiant at varying primary air-gas ratios. (See Table 5.) In the tests the gas rate was maintained at about 15 cubic feet per hour, and samples of gas were taken 1 inch from the bottom of the radiant, as near the center as possible. The samples were rapidly withdrawn through a silica tube of very small diameter to prevent secondary reactions. Temperatures were taken at the same point for comparison of temperature with change of air-gas ratio. It is realized that with the method used the temperature measurements may not be very accurate, because of the effect of radiation, but the results will serve for comparative purposes.

TABLE 5.—*Composition and temperatures of the gases in a glowing radiant*[1]

Test No.	Gas rate per hour	Orifice pressure of water	Air-gas ratio	Composition of gas in radiant just above first blue inner cone, per cent by volume						Temperature at point where sample was taken[2]		Remarks
				CO_2	O_2	H_2	CO	CH_4	N	° C.	° F.	
	Cubic feet	*Inches*										
1	15.2	6.5	11.5	9.5	4.3	0.0	0.1	0.0	86.1	1,093	2,000	Highest air-gas ratio at which heater could be operated at this gas rate.
3	15.3	4.5	8.8	9.8	1.0	.8	2.0	.0	86.4	1,141	2,085	Short and sharp; blue inner cones.
5	15.3	2.5	8.0	8.4	.9	2.6	4.4	.1	83.6	1,124	2,055	Do.
6	15.0	1.5	7.3	7.4	.3	4.8	6.6	.1	80.8	1,074	1,965	Blue inner cones, long.
7	15.1	(3)	7.2	6.9	.2	5.7	7.2	.0	80.0	-------	-------	Primary air opening closed with asbestos sheet.
8	15.2	(3)	6.6	3.5	7.0	4.5	5.7	5.6	73.7	-------	-------	Blue inner cone extended above point where sample was taken.

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[1] Gas rate was kept constant and only air-gas orifice pressure. The samples were taken from the center of the radiant at the bottom and a short distance above the blue inner cone.

[2] Temperatures given were obtained with a Hoskin alumel-chromel couple, and subject to errors due to radiation, etc. The values are given for comparative data only.

[3] No orifice pressure taken, as primary air opening was closed with asbestos, thus invalidating the effect of orifice pressure.

RESULTS OF TESTS

The first sample (test 1) was taken after the heater was adjusted to give the highest air-gas ratio possible and still operate satisfactorily. The air-gas ratio for this test was 11.5, or more than enough to give complete combustion (10.2 is required to give complete combustion with the natural gas used in the test). The gas taken from the radiant showed (Table 5) that combustion was practically complete, and an excess of oxygen was present. The sample was taken not over 1 inch above the burner ports and is remarkable in that it shows how quickly combustion occurs if enough air is present to consume the gas. If enough air is present, combustion takes place and is completed in the first inch of travel from the burner ports, and the glowing of the remainder of the radiant is not due to the burning gas, but rather to the luminescence of the glowing radiant, which has absorbed heat from the combustion products and heated gases.

In test 3, taken at the same place, the air-gas ratio was reduced to 8.8, or below that for complete combustion. In this test secondary air was necessary to complete the combustion. The gases contained 2 per cent of carbon monoxide and 0.8 per cent of hydrogen, but no methane. The oxygen also was reduced to 1 per cent. These incomplete combustion products had to travel farther up the interior of the radiant until the gases began to cool, causing secondary air to be drawn into the radiant; thus combustion was completed.

Tests 5, 6, and 7 were very similar to test 3, but the incomplete combustion products were present in larger amounts, due to the reduced air-gas ratio. The lower the air-gas ratio the greater the amount of incomplete combustion products (carbon monoxide and hydrogen) present, and the farther the gas must travel up the interior of the radiant before secondary air enters to complete the combustion. On this basis the lower the air-gas ratio the longer the radiant should be to give complete combustion at any gas rate. What really happens in a heater using radiants of the present size is that for a given gas rate, as the air-gas ratio decreases, the point where complete combustion occurs rises higher and higher until the top of the radiant is reached, when the gases pass out; and if chilled they are only partly burned and liberate carbon monoxide.

In test 8 the air-fuel ratio was so low (6.6) that the blue inner cone elongated and spread out, and this sample showed combustion products in which the gas has only partly reacted with the oxygen. A large percentage of oxygen and natural gas was present, and smaller amounts of carbon monoxide and hydrogen.

CHARACTERISTICS OF THE GASES FROM GLOWING RADIANTS

The gases taken from the glowing radiant show a few interesting points, as follows:

1. When supplied with less air than is necessary for complete combustion, the gases inside a glowing radiant above the blue inner cone consist mainly of carbon dioxide, carbon monoxide, water vapor, and hydrogen, and little, if any, methane. The resulting temperature produced is enough to decompose the original gas completely into simpler products, such as carbon dioxide, carbon monoxide, and hydrogen.
2. When the amount of primary air introduced with the gas is enough to give complete combustion, the reactions are completed a very short distance from the burner ports—within 1 inch at a gas rate of 15 cubic feet.
3. The prettiest glow does not indicate the most complete combustion. When just the correct amount of air is added to give complete combustion the flame is essentially nonluminous, and only the glowing of the radiants is seen.
4. The extension of the blue inner cones up through the radiants indicates a low air-gas ratio and the liberation of products of incomplete combustion.

To illustrate the danger if the combustion gases in test 6 were suddenly chilled and escaped into the room without burning, the total carbon-containing gases—that is, CO_2, CO, and CH_4—equal 14.1 per cent, of which $\frac{7.2}{14.1}$, or 51 per cent, is carbon monoxide.

SUGGESTIONS FOR A WELL-DESIGNED HEATER OF TYPE 4

Figure 4 shows a few conditions that should be observed in the construction and operation of radiant-type heaters. They may be summarized as follows:

1. The orifice *a* should be only large enough to make the radiants glow three-fourths the distance from bottom to top, as viewed in the daylight when all adjustments are wide open with the maximum gas pressure available.

2. The air-injecting tube *b* should be correctly designed to give a high primary air-gas ratio (at least 8 to 1) at the gas rates and gas pressures at which it may be operated.
3. The burning gas *c* should give very short sharp blue inner cones. An elongated inner cone indicates a low air-gas ratio and improper adjustment.
4. Primary air-adjusting devices *e* should not be used, as they might be easily closed—for example, while the under part of the heater is being cleaned. If the primary air valve is closed, dangerous quantities of carbon monoxide are produced.

DESIGN OF ORIFICES, AIR INJECTORS, AND RADIANTS

This report has not discussed the style and design of orifices. The point to be remembered is that the orifices should not be too large. Some heaters are sold with fixed and some with adjustable orifices. Few people understand the proper adjustment and operation of these devices, which may be dangerous unless used intelligently. If adjustable orifices are supplied, they should always be small enough so that, at the maximum opening, an excessive flow of gas can not be obtained at the maximum gas pressure at which they may be used. The design of orifices has been very carefully worked by the Bureau of Standards[8] in its report on "Atmospheric gas burners," to which the reader is referred.

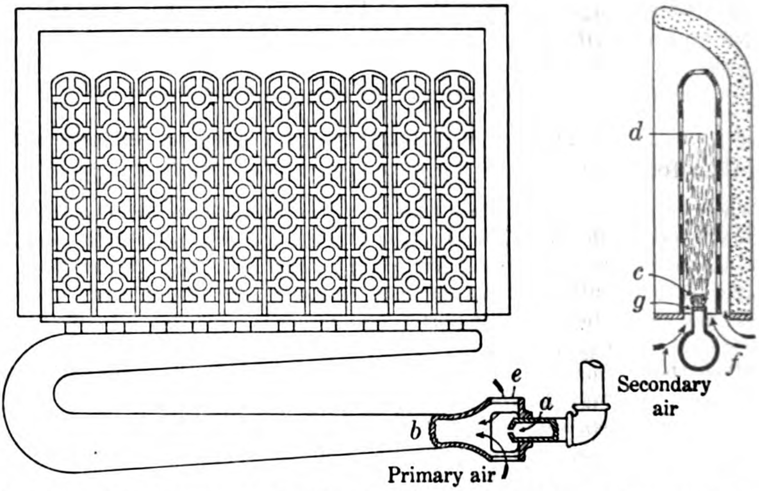

FIGURE 4.—A well-constructed, radiant-type, nonluminous-flame natural-gas heater

The design of air injectors to give the proper air-gas ratio is also given in the Bureau of Standards paper. The amount of primary air that is entrained with the gas necessitates careful design of the air injector, ratio of the port area to throat area, position and shape of the gas orifice, and density and pressure of the gas used.

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[8] Berry, W. M., Brumbaugh, I. V., Moulton, G. F., and Shawn, G. B., work cited.

Extensive research is necessary before the relation of size and shape of radiants in radiant-type heaters to liberation of carbon monoxide can be determined. Future change of design may change many of the conclusions given in this report.

SUMMARY

Results of Bureau of Mines test of house heaters (heaters for warming rooms) burning natural gas, to determine (1) what types as usually operated give incomplete combustion products, (2) why there is incomplete combustion, and (3) how by proper adjustment or change in design the different types can be made to operate more efficiently are in brief as follows:

Every natural-gas heater tested would liberate carbon monoxide under certain operating conditions.

Products of incomplete combustion are due to one of the following: 1, The heater has not been designed by the manufacturer to give good combustion; 2, the heater is properly designed by the manufacturer to give good combustion at certain gas flows and gas pressures, but is not flexible enough to burn efficiently under widely varying gas flows and gas pressures; and 3, the heater is properly designed by the manufacturer, and is very flexible in operation, but users can too easily change the adjustments, so that the primary air-gas ratio is reduced or the gas flow increased beyond the safe capacity of the heater.

Formation of incomplete combustion products is primarily caused by restricting the air supply to the burning gas either because of faulty construction of the heater or because adjustments are so made that enough oxygen does not reach the flame to give complete combustion.

SUGGESTIONS FOR OBTAINING EFFICIENT COMBUSTION

More efficient combustion can be obtained by observing the following precautions:

A yellow-flame heater should be so operated that the flame does not impinge on any metal or other surface and should burn in such a manner that plenty of air gets to the burning gas.

A blue-flame reflector heater (see p. 10 for description) should inject 4 or more volumes of air with the gas before the gas reaches the burner ports; in turn the burning gas should be supplied with an abundant amount of secondary air to complete the combustion. Any attachments that would restrict the supply of secondary air, such as guards without openings over the front of the heater, should be removed.

A blue-flame metal-inclosed heater (see p. 11 for description) should have an orifice so small that the flames can not pass through the metal grid even when the gas cock is wide open at the highest gas pressure available.

A radiant heater (see p. 13 for description) should have a gas orifice only large enough to make the radiants glow three-fourths the distance from bottom to top as viewed in the daylight, or within 1 inch of the top as viewed in a darkened room, when all adjustments are wide open at the maximum gas pressure available.

The air-injecting tube should entrain 8 or more volumes of air with the gas before the gas reaches the burner ports at the gas pressures and gas rates at which it may be operated. The burning gas should give very sharp blue inner cones. If the heater is equipped with a primary-air-adjusting device it should be kept as wide open as possible, so as not to reduce the amount of primary air injected with the gas. When possible the gas flow should be regulated from the needle valve rather than from the gas cock.